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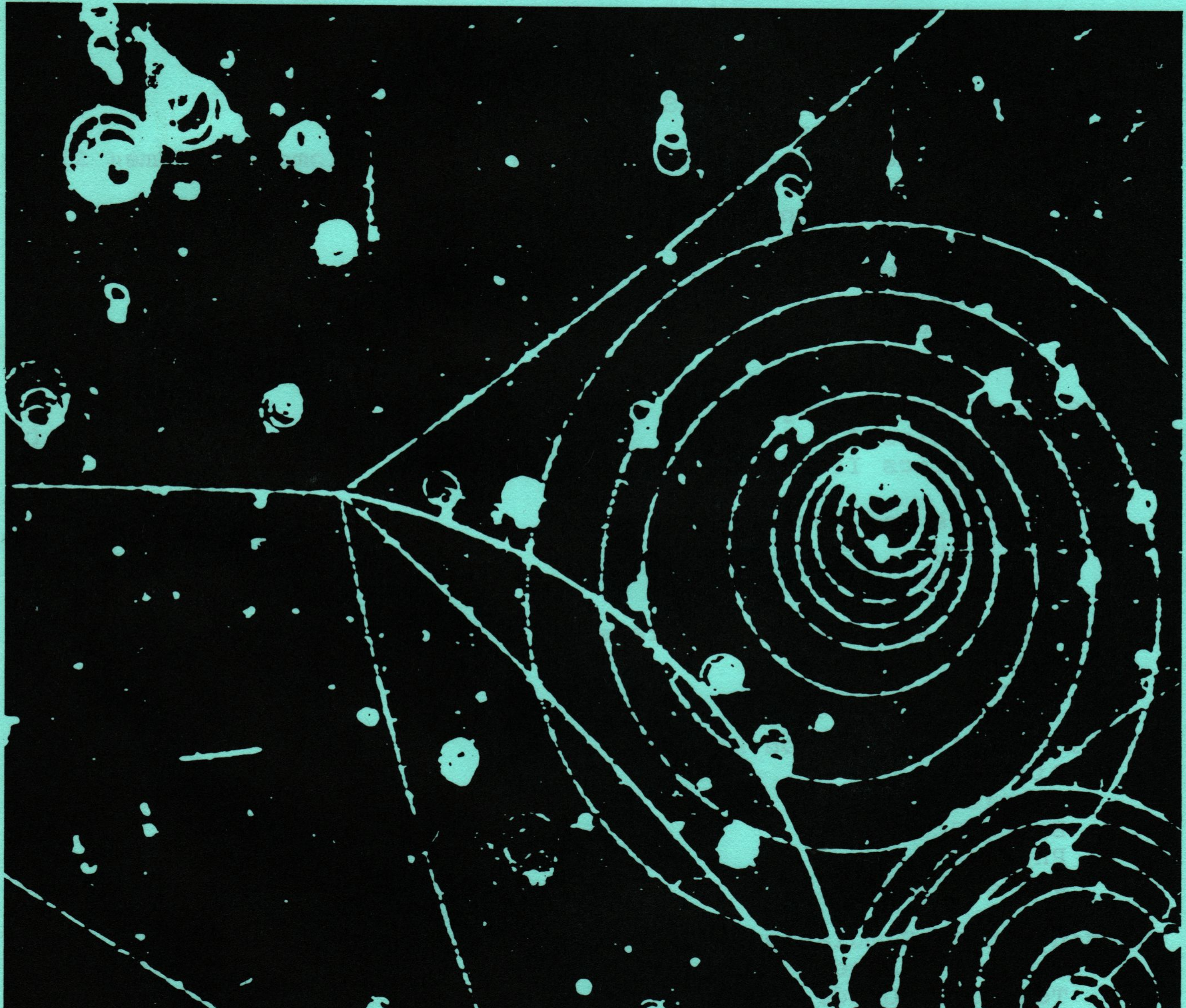

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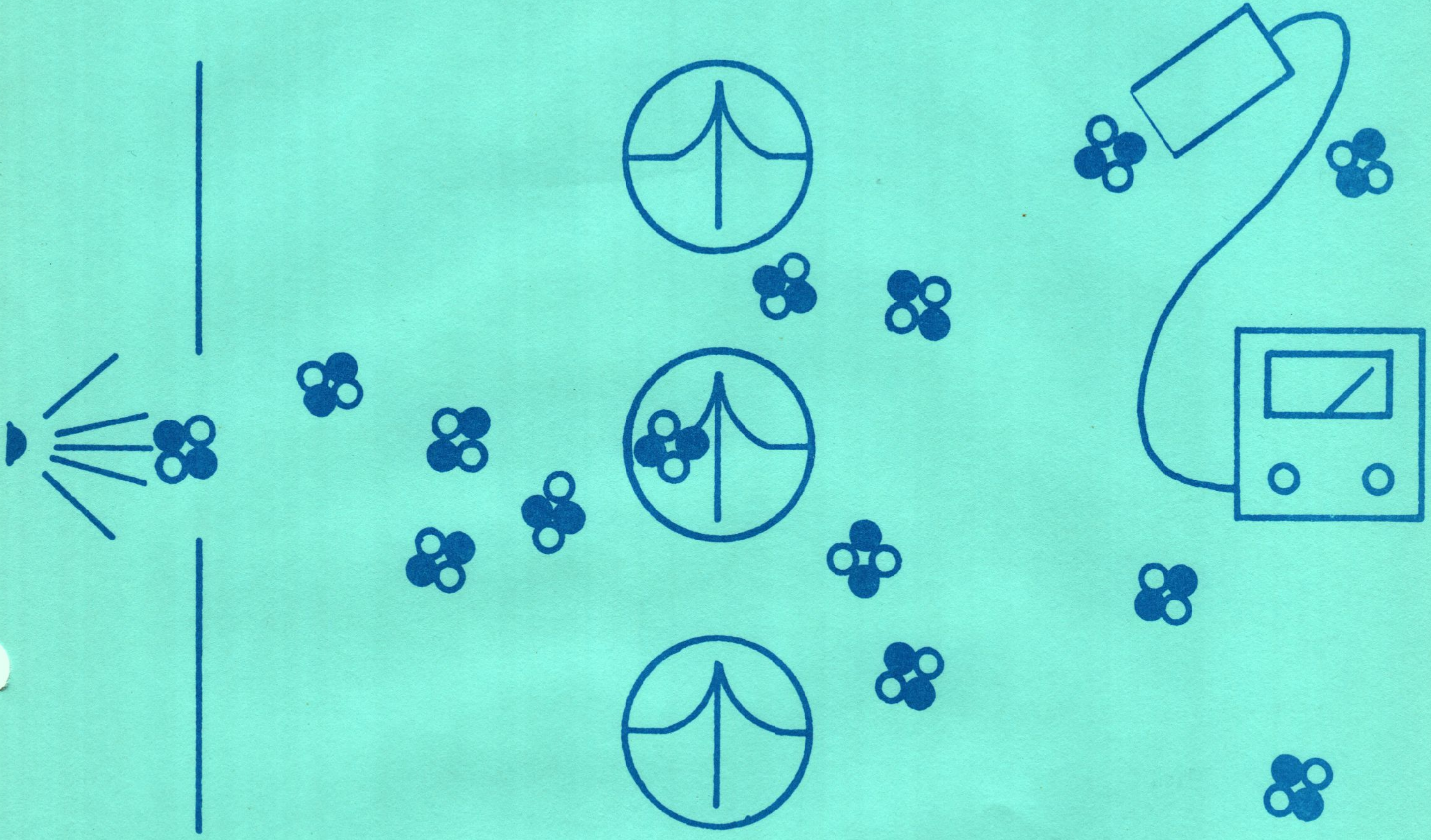
SCATER



Student Manual

A computer simulation of the use of alpha particle scattering to determine atomic structure

HUNTINGTON TWO COMPUTER PROJECT

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SCATER

STUDENT MANUAL

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I. INTRODUCTION TO *SCATER*

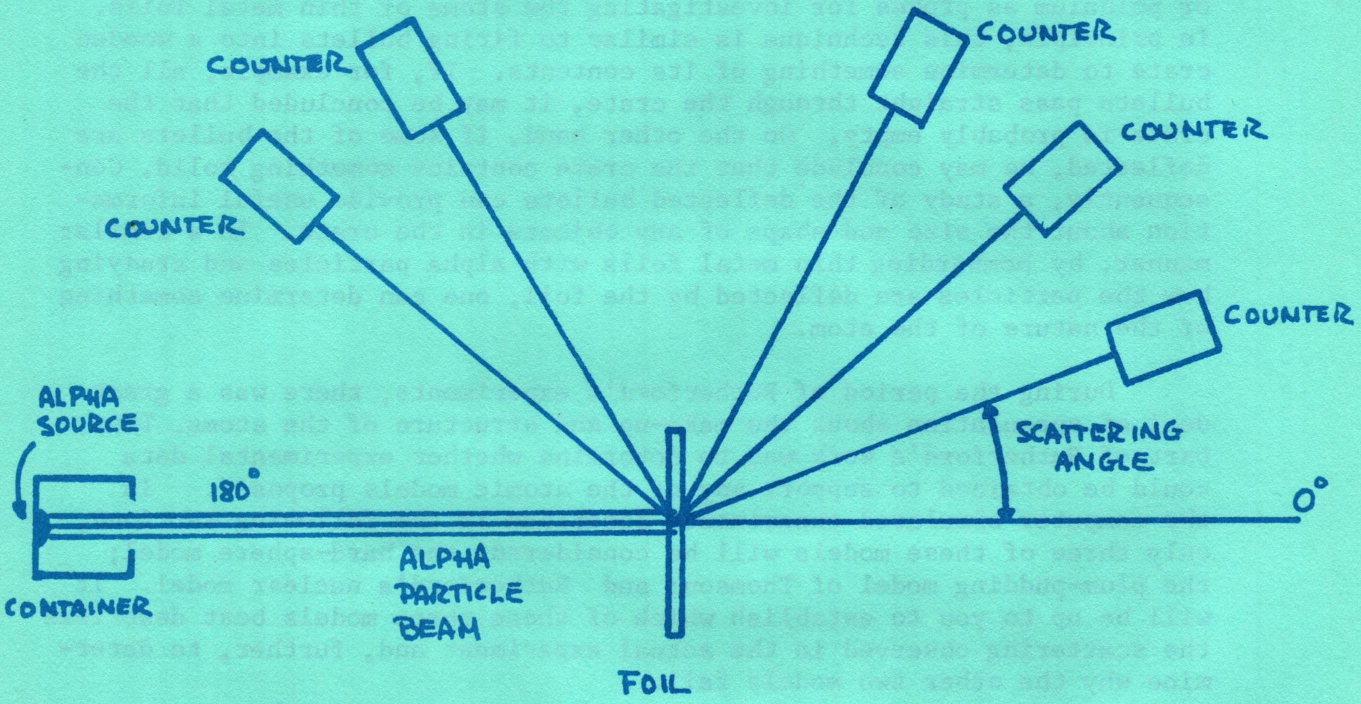
How can we determine the structure of the atom when, individually, the atoms are too small to touch or see? Obviously, direct studies are impractical, so that indirect or secondary methods must be used. Ernest Rutherford found that he could use the alpha particles emitted by radium or polonium as probes for investigating the atoms of thin metal foils. In principle, this technique is similar to firing bullets into a wooden crate to determine something of its contents. If, for example, all the bullets pass straight through the crate, it may be concluded that the crate is probably empty. On the other hand, if some of the bullets are deflected, we may conclude that the crate contains something solid. Consequently, a study of the deflected bullets can provide useful information about the size and shape of any objects in the crate. In a similar manner, by bombarding thin metal foils with alpha particles and studying how the particles are deflected by the foil, one can determine something of the nature of the atom.

During the period of Rutherford's experiments, there was a great deal of speculation about the make-up and structure of the atoms. Thus, part of Rutherford's work was to determine whether experimental data could be obtained to support any of the atomic models proposed. In the computer simulated experiments described in the following sections, only three of these models will be considered: the hard-sphere model; the plum-pudding model of Thomson; and Rutherford's nuclear model. It will be up to you to establish which of these three models best describes the scattering observed in the actual experiment and, further, to determine why the other two models fail.

II. USING THE *SCATER* PROGRAMS

SCATR1 -- THE EXPERIMENT

SCATR1 is a simulation of an actual laboratory experiment on alpha particle scattering. An alpha particle source is placed in a container so that the emerging alpha particles form a beam. The beam strikes a thin metal foil. When the alpha particles strike the foil, some of them will be scattered in collisions with the atoms of the foil. To detect the scattered particles, five particle counters are placed at specified angles with respect to the incident beam. All of the counters are the same size and the same distance away from the foil.



By varying the positions of the counters, the number of particles scattered through any angle can be determined.

When running the simulated experiment, you can specify the location of the five counters. That is, you can select angular locations between 10° and 180° with respect to the incident beam for each counter. Following this selection, the computer will print out the number of particles counted during a fixed time period by each counter. The machine will then request five new counter locations by typing "C(1)=?", "C(2)=?", etc. This process can be continued until you collect sufficient data to plot a reliable "angular distribution" curve (the angular distribution simply refers to the proportion of particles scattered through each angle) as on the following graph form:

```
              FRACTION OF PARTICLES SCATTERED (LOG SCALE)

         1E-9      1E-8      1E-7      1E-6      1E-5      1E-4      1E-3
ANGLE:   I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I
   0    I
  10    I
  20    I
  30    I
  40    I
  50    I
  60    I
  70    I
  80    I
  90    I
 100    I
 110    I
 120    I
 130    I
 140    I
 150    I
 160    I
 170    I
 180    I
         I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I
```

The dots on this logarithmic scale, from left to right in each interval, stand for 2, 4, 6, and 8, respectively. For example, if we are referring to the left-most interval, the first dot represents a value of $2x10^{-9}$, the second dot a value of $4x10^{-9}$, etc.

It will be easier to compare the experimental data with theoretical predictions if you plot the fraction of particles scattered at each angle rather than the number of particles. The fraction scattered is calculated by dividing the number scattered by the total number of alpha particles striking the foil during the counting period.

For those angles at which there are very few counts, statistical fluctuations of the number of particles entering the counters will make the number of counts fluctuate from RUN to RUN. If N is the total number of counts detected by a counter, the fluctuation to be expected is approximately equal to the square root of N. That is, a counter that gives a reading of 50 counts could be expected to read between 43 and 57 counts if the experiment were run again.

The program can be ended by typing "4" when the computer asks "C( )=?".

SCATR2 -- THEORETICAL PREDICTIONS

To determine which of the three proposed models best agrees with the real situation, you will have to compare the data collected during the simulated experiment with the results predicted by each of the three models. In this part of the program, it is assumed that the alpha particles from the source strike the foil uniformly and are scattered by one of the three hypothetical atomic models. The theoretical scattering results are plotted by the computer for angles of 10^o, 20^o, ... 180^o.

The first inputs requested during this part of the program are the energy of the alpha particles, the material of the foil, the thickness of the foil, and the size and distance of the counters. Choose values that are the same as those used in the experiment in *SCATR1*.

(When exploring the effect of other values of these quantities, the limits that the computer will accept are:

Alpha particle energies between 2 and 8 MeV.

Foil thickness between .5 and 2 micrometers
(1 micrometer = 1E-6 meters).

Counter size between .5 and 2 cm^2.

Counter distance between 10 and 40 cm.)

The computer will type a request for input in the form:

```
ENERGY = 2.2?
```

The number following the name of the quantity is the value presently in the machine. The number you type after the question mark (?) will become the new value.

The next input selects which of the three theoretical models the computer will use to calculate the angular distribution. After the computer types "MODEL", any of the following number codes may be typed into the machine:

"1" for the hard-sphere model

"2" for the Thomson (plum-pudding) model

"3" for the Rutherford (nuclear) model.

Using the chosen model, the theoretical prediction of the fraction of alpha particles scattered through the various angles will be plotted.

When the computer finishes printing the predicted graph, the request "NEXT PREDICTION" can be answered by:

"1" to change the model

"2" to change the energy, foil, or counter size and distance

"3" to end the program.

By selecting each of the theoretical models in turn, you can obtain graphs of the angular distribution of scattered alpha particles predicted by each model. The experimental results of *SCATR1* can be compared directly with the computer-predicted graphs of *SCATR2* for each model. Which model is most likely to be an accurate picture of the structure of atoms?

SCATR3 -- TRAJECTORIES

Comparison of the angular distribution graphs generated for each model of the atom in *SCATR2* with the results of the actual laboratory experiment in *SCATR1* will enable you to confidently identify a reliable model of the atom. But *SCATR2* tells you nothing about how these angular distribution graphs were produced.

SCATR3 was developed to allow you to explore the mechanics of the scattering process on the level of individual atoms and alpha particles.

In *SCATR3*, the trajectories of three alpha particles fired at a single Rutherford-type target atom are plotted. Since you can locate the initial position of each alpha particle with respect to the center of the target atom, you can study how a Rutherford-type atom deflects the incident particles.

Changes in the alpha particle energy and in the material of the foil change the theoretical prediction of how alpha particle paths are deflected by atoms. Since in an actual scattering experiment the perpendicular distance between the incident alpha particles and the center of the atoms in the foil cannot be controlled (the atoms are only about 10^{-8} cm in diameter), alpha particles are incident at all distances from the atomic center and this is taken into account in calculating the theoretical number of alpha particles that are scattered at each angle (as in *SCATR2*). It is not always easy to see how a set of trajectories leads to a predicted angular distribution (it takes some careful reasoning and mathematics); but some features of the angular distribution predicted from each model can be seen by investigating the trajectories.

The first inputs requested are the alpha particle energy and the target material. The energy limits are again 2 to 8 MeV. Following the selection of the energy and material, you can indicate the initial positions of three alpha particles: X(1), X(2), and X(3). X(1), X(2), and X(3) are the "impact parameters" and measure the distance from the center of the target atom (which is at zero along the x-axis) to the point along the x-axis from which each alpha particle is fired. An impact parameter measures how close to the center of the atom an alpha particle would come if it were not deflected. Alpha particles with different impact parameters will be scattered through different angles.

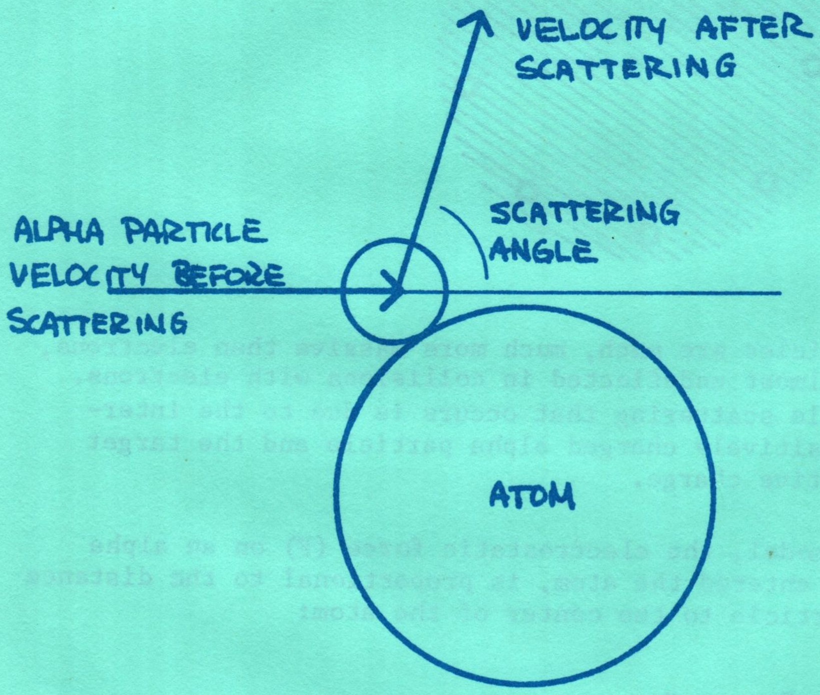
The computer will accept values of impact parameter between -200,000 and +200,000 femtometers (1 femtometer = 10^{-15} meters). It will then plot a picture of three alpha particles scattering from a Rutherford atom. The trajectory of each alpha particle is indicated by the particle number. A circle of B's shows the boundary of the entire atom and an N marks the position of the atomic nucleus. Distances along both axes of the picture are measured in femtometers.

The angle between the continuation of the line of approach of the alpha particle and its line of departure from the target atom is the angle of scattering, the angle which would be recorded by the counters. The angle of scattering of the three alpha particles is printed at the bottom of the picture. It's easy to see that the scattering angle is very small unless the alpha particle passes within a few hundred femtometers of the atomic nucleus. After viewing a number of trajectories, try to connect the individual trajectories and the angles of scattering with the "big picture" of the angular distribution.

III. THE MODELS

The Hard-Sphere Model

In this model, atoms are assumed to be hard spheres that are electrically neutral, somewhat like bowling balls. The alpha particles are thought of as smaller, billiard ball-like spheres. Imagine a moving billiard ball hitting a heavy bowling ball that is standing still; the bowling ball is almost unmoved by the collision, while the billiard ball bounces away with almost its original speed. (The fact that the bowling ball is almost unmoved means that there is very little transfer of kinetic energy between the balls, so the billiard ball has almost the same amount of kinetic energy -- and therefore almost the same speed -- after the collision as it did before.)

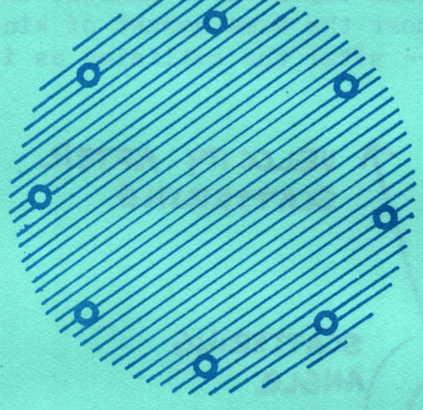

VELOCITY AFTER SCATTERING
SCATTERING ANGLE
ALPHA PARTICLE VELOCITY BEFORE SCATTERING
ATOM

The hard-sphere model, as used in *SCATR2*, assumes that both the target atom and the alpha particle are to be considered hard spheres, with the target atom much more massive than the alpha particle. However, each of the target spheres is assumed to be transparent enough so that most of the alpha particles go straight through and only one in 100,000 of them bounce off.

The Thomson Model (Plum-Pudding Model)

The electron was discovered in 1897 by J. J. Thomson. Nine years later the positive charge carrier of an atom was identified as having a charge equal and opposite to that of the electron but with a much greater mass. This too was accomplished by Thomson.

During this time Thomson proposed a model of the atom. This atom was a sphere of positive charge in which the negatively charged electrons were imbedded in rings, like "plums floating in a pudding." The atom as a whole was assumed to be electrically neutral and mechanically stable.



Since alpha particles are much, much more massive than electrons, alpha particles are almost undeflected in collisions with electrons. The only alpha particle scattering that occurs is due to the interaction between the positively charged alpha particle and the target atom's sphere of positive charge.

In the Thomson model, the electrostatic force (F) on an alpha particle, once it has entered the atom, is proportional to the distance (r) from the alpha particle to the center of the atom:

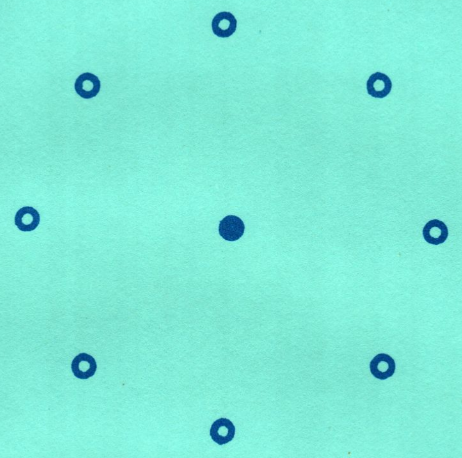
$$F = \left[k \frac{Qq}{R^3} \right] r$$

(Q is the charge of the target atom; q is the charge of the alpha particle; R is the radius of the target atom; and k is a constant that depends on the choice of units.)

The force is greatest near the outer edge of the atom where r is largest, but never becomes great enough to scatter the alpha particle through any angle greater than a few degrees.

The Rutherford Model (Nuclear or Planetary Model)

A nuclear or planetary model of the atom was proposed by Ernest Rutherford in 1911. The model assumed a small, positively charged nucleus at the center of the atom with almost all of the atom's mass concentrated in the nucleus. The negatively charged electrons were thought to revolve in orbits about the nucleus, with most of the volume of the atom empty space. The atom as a whole was electrically neutral.



The Rutherford model of the atom is the third used in the scattering programs. Because the electrons are too light to deflect an alpha particle, all alpha particle scattering is due to a Coulomb force of repulsion between the positively charged alpha particle and the positively charged nucleus. This force, F, is given by:

$$F = \left[k\ Q\ q \right] \frac{1}{r^2}$$

where Q is the nuclear charge of the atom; q is the charge of the alpha particle; r is the distance from the alpha particle to the center of the atom; and k is a constant that depends on the units.

When r, the distance from the alpha particle to the center of the atom, gets very small, the force on the alpha particle gets very large and deflects the alpha particle through a large angle.